PB84-130442

Analysis of Residential Coal Stove Emissions

Battelle Columbus Div., OH

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

Dec 83

U.S. Department of Commerce
National Technical Information Service
NTIS

PB84-130442

EPA-600/7-83-060
December 1983

ANALYSIS OF RESIDENTIAL COAL STOVE EMISSIONS

by

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Contract Number 68-02-3169
Work Assignment 29.0

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Prepared for:

OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
Washington, DC 20460

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-83-060	2.
3. RECIPIENT'S ACCESSION NO. PB84 130442	
4. TITLE AND SUBTITLE Analysis of Residential Coal Stove Emissions	5. REPORT DATE December 1983
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Marcus Cooke, W.E. Bresler, R.B. Iden, T.L. Hayes, and S.E. Rogers	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Battelle-Columbus Laboratories 505 King Avenue Columbus, Ohio 43201	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO. 68-02-3169, Task 29
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED Task Final; 6/82 - 7/83
	14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is Michael C. Osborne, Mail Drop 65, 919/541-4113.

16. ABSTRACT The report gives results of an evaluation, in cooperation with the State of Vermont's Agency of Environmental Conservation, of emissions generated by anthracite and bituminous coal used for residential heating. A residential coal stove was operated with both coals, while comparing high and low burn rate operations. A second stove, a commercial stove designed for wood burning but modified by the manufacturer for coal, was also tested with both coals. Combustion gases were collected by two techniques: evacuated glass bulbs and a Modified Method 5 sampling train. Volatile species were analyzed by direct gas mass spectrometry and by gas chromatography using selective detectors. Polynuclear aromatic hydrocarbons (PAHs) were analyzed by high resolution gas chromatography/mass spectrometry. High levels of particulates, total organics, and sulfur dioxide were found in the emissions from bituminous coal combustion in a residential coal stove. High PAH emissions were found with both bituminous and anthracite combustion. The stove converted from wood to coal burning proved to be highly polluting, especially when used with bituminous coal.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Coal	Stationary Sources	21D
Combustion	Wood Stoves	21B
Stoves		13A
Space Heaters		
Analyzing		14B

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 35
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

NOTICE

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ABSTRACT

This study was performed in cooperation with the State of Vermont, Agency of Environmental Conservation. The goal of the program was to evaluate emissions generated by anthracite and bituminous coal used for residential heating. A residential coal stove was operated with both coal fuels while comparing a high burn rate condition, with low burn rate operation. A second stove, a commercial stove designed for wood burning and modified by the manufacturer for coal, was also tested with both coal types. Combustion gases were collected by two techniques: evacuated glass bulbs, and a Modified Method 5 sampling train. Volatile species were analyzed by direct gas mass spectrometry and by gas chromatography using selective detectors. Polynuclear aromatic hydrocarbons were analyzed by high resolution gas chromatography/mass spectrometry.

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ACKNOWLEDGMENTS

The authors would like to express their appreciation for the assistance and technical help of Cedric R. Sanborn, Air Pollution Control Engineer, State of Vermont, Agency of Environmental Conservation (Montpelier, Vermont). In addition to participating in program planning, Sanborn erected the stoves and operated the residential test appliances throughout the test. Without his willing and competent contribution, this coal stove study would not have been possible.

In addition thanks are given to the EPA Task Officer, Michael C. Osborne, whose technical guidance and supervision of the field sampling experiments were instrumental in the successful completion of the program.

The participation of several Battelle staff members is gratefully acknowledged; Cheng Chen Chuang for GC/MS data computation, Robert L. Livingston for gas mass spectral analyses, and Maria B. Dean for secretarial assistance.

SECTION 1

INTRODUCTION

This study was a cooperative program with the Vermont Agency of Environmental Conservation. Some interest has been shown in the Northeastern United States about the effects of coal combustion in residential appliances, especially stoves designed to use wood then retrofitted for coal. These stoves may not contain the proper engineering criteria for clean operation when burning coal fuel especially Eastern bituminous coal. The State of Vermont has instituted a detailed residential research program under the direction of Cedric R. Sanborn, Air Pollution Control Engineer, to evaluate impacts of coal combustion in the home. Mr. Sanborn enlisted the participation of EPA to measure pollutant discharge levels during a series of stove tests scheduled for the Fall of 1982. The following table gives a summary of the tests conducted.

TABLE 1. STOVE TESTS

Unit	Fuel	
Converted Coal/Wood Stove (low burn rate)	Bituminous	Anthracite
Residential Coal Stove (high burn rate)	Bituminous	Anthracite
Residential Coal Stove (low burn rate)	Bituminous	Anthracite

Residential coal-fired, stoker-fed furnaces were tested in an earlier EPA program in which Western bituminous and subbituminous coals were used in two

200,000 Btu/hr residential furnaces (1). This study concluded that particulate discharges are a function of organic content (not inorganic ash) in residential coal combustion. The authors cited the low efficiencies of small residential combustion systems to explain this effect. Sulfur oxide concentrations followed fuel sulfur levels in that study and carbon monoxide levels were highly variable (0.04 Kg/ton to 12 Kg/ton fuel). Several polynuclear aromatic hydrocarbons were identified, generally at very high discharge concentrations, e.g., fluoranthene at 22 ppm (W/W fuel basis). In an EPA study, to measure emissions from large commercial coal-fired stoker boilers, much lower PAH emission levels were observed (2,3). The average fluoranthene concentration, including methylpyrene isomers, was 1.5 ppb (W/W fuel basis). Thus, in the Vermont study it was of interest to investigate emissions of small residential stoves and compare these emissions with those of the larger systems previously tested.

A primary goal of this study was to investigate the levels of criteria air pollutants and hazardous organic constituents found in small residential coal-fired stoves when operated in a manner characteristic of home heating. The stoves investigated in this program operated from 22,000-57,000 Btu/hr compared to an average of 200,000 Btu/hr for the earlier mentioned EPA residential coal furnace study (4). The stoves tested in the Vermont study are characteristic of small hand-stoked stoves used in the United States for residential space heating.

SECTION 2

RECOMMENDATIONS

High levels of particulates, total organics, and sulfur dioxide (SO_2) were found in the emissions from bituminous coal combustion in a residential coal stove. The high levels of SO_2 found with anthracite combustion may indicate that treated fuel such as cleaned coal or coal pelletized with a sulfur slagging agent such as limestone may be of interest to reduce SO_2 emissions.

High PAH emissions were found with both bituminous and anthracite combustion. The elevated levels found when burning bituminous fuel are especially significant since benzo(a)pyrene, a known mammalian carcinogen, is one of the PAH compounds that is shown to be emitted.

The stove converted from woodburning to coal use was proved to be highly polluting especially when used with bituminous coal. Additional research is necessary to determine if the constrained air situation and firebox design of this stove can be made "clean burning".

SECTION 3

EXPERIMENTAL PROCEDURES

Emissions samples were collected during combustion tests conducted in October, 1982, at the residence of Cedric Sanborn in Barre, Vermont. Two stoves were used in the tests. One of the stoves was designed by the manufacturer for coal combustion. This stove was operated in a high burn rate mode and an air-starved mode which generated a low burn rate. The second stove was primarily designed for wood combustion but had been modified by the manufacturer to accommodate coal. The narrow damper on this modified wood stove constricted combustion air and consequently this stove could only be tested at low burn rates. Each stove was tested with anthracite and bituminous coal to evaluate the effect of the two fuels on emissions.

Analyses included fixed combustion gases, condensible organics, Method 5 particulates, principal volatile compound screening by gas mass spectrometry (GMS), and polynuclear aromatic hydrocarbon (PAH) analysis by high resolution gas chromatography/mass spectrometry (GC/MS).

SAMPLING PROCEDURES

Samples were collected for fixed gas and volatile organics analysis using evacuated glass bulbs. Three liter glass sampling bulbs were prepared at Battelle by evacuating to approximately 10^{-6} torr pressure and heating to drive off residual moisture. After preparation, the sample bulbs were wrapped with foam insulation and shipped to the experimental site in Vermont. The gas samples were taken by inserting a stainless steel probe through a sample port located approximately 1 foot up the vertical section of the stove exhaust stack. A sample was collected by opening the stopcock on the evacuated sample bulb during steady state combustion.

PAH and particulate sampling was conducted with an EPA Modified Method 5 sampling train. This system, shown in Figure 1, has been used by Battelle on a wide variety of programs including industrial and residential coal combustion systems.

The Method 5 sampling train separates the sample into a particulate fraction in the heated probe and filter section, and a semivolatile organics fraction which collects on the resin. The XAD-2 resin material was extracted along with the particulate-laden filter in a Soxhlet extractor using methylene chloride. The filter was re-extracted separately with benzene to remove PAH compounds not extracted by methylene chloride. The resin-filter extracts were combined with the extracted aqueous impinger samples to produce a combined organics sample. The combined extract was analyzed by gas chromatography and gravimetry to determine condensible organics. This extract was also used for PAH analyses.

ANALYTICAL PROCEDURES

Fuel and Gas Analyses

Fuel analyses were provided by the Vermont Agency of Environmental Conservation. Standard ASTM procedures were used to generate elemental analyses (C-H-N-O-S), ash, volatiles, fixed carbon, moisture and heating value (dry basis).

Fixed gas analyses were performed on the glass bulb samples. Samples were analyzed using a combination of mass spectrometry and three gas chromatographic techniques. A Consolidated Electrodynamics Corporation, Model 21-620, mass spectrometer was used for a general analysis from mass 2 to 100. Since the mass spectrometer does not separate carbon monoxide and nitrogen, the carbon monoxide was determined using an Aerograph, Model 202, gas chromatograph with a molecular sieve column and a thermal conductivity detector.

Low molecular weight hydrocarbons and sulfur gases were determined using a Varian, Model 3700, gas chromatograph. A Poropak Q column with a flame ionization detector was used in the hydrocarbon analyses and a Supelco S column with a flame photometric detector was used for the sulfur gases.

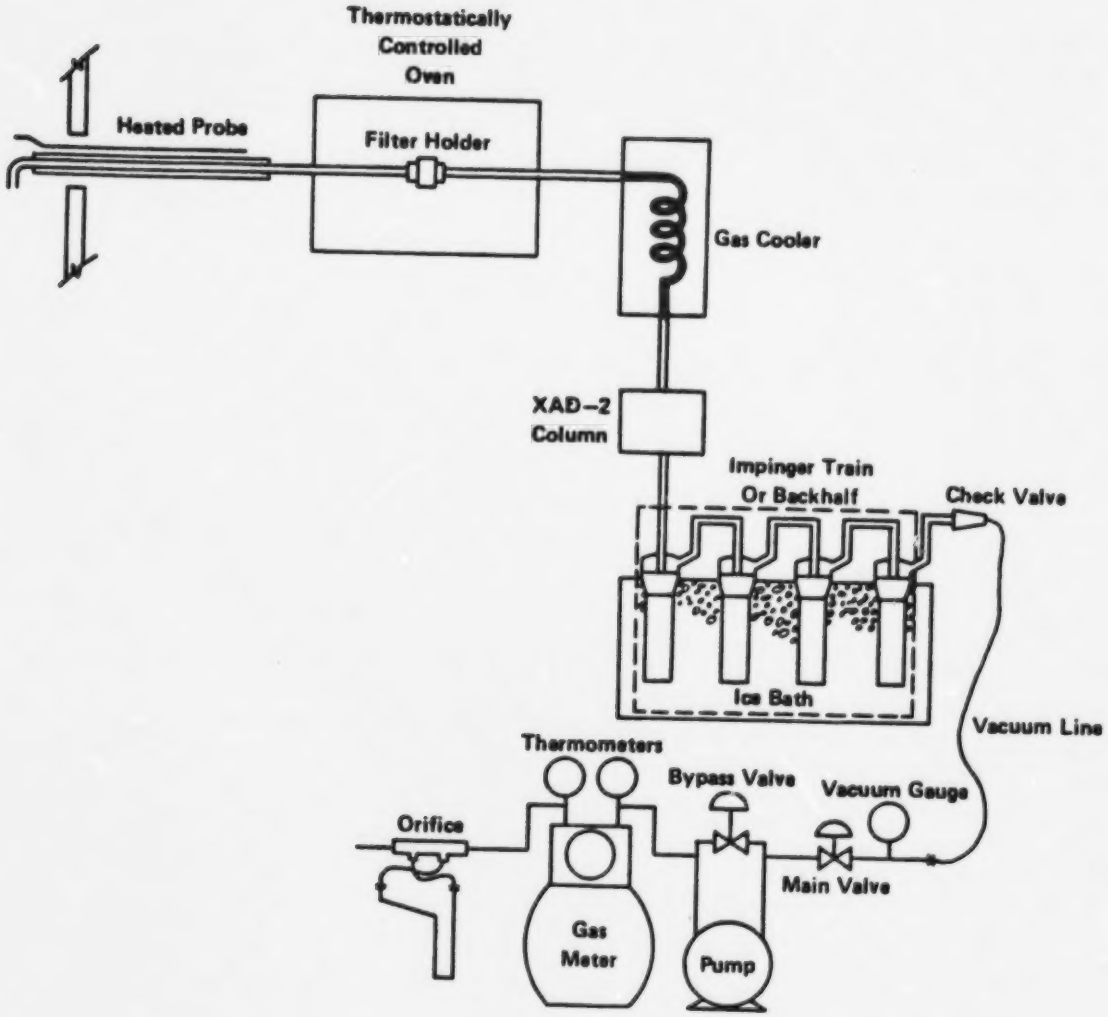

FIGURE 1. PARTICULATE AND PAH SAMPLING SYSTEM.

Condensible Organics Analyses

Condensible organics were measured by extracting the Method 5 particulates and the XAD-2 resin bed with methylene chloride and performing a gravimetric analysis (GRAV) on the extracts. This procedure is described in EPA's Level 1 manual for characterization of source discharges (5). The gravimetric analysis measures the mass of extracted material. This analysis does not measure volatile species, in fact most volatiles are lost by the Method 5 sampling train. The evacuated gas bulbs are useful in estimating principal volatile organics.

PAH Analyses

The filter/resin extraction yielded two extracts: a methylene chloride extract which contained most of the organic burden, and a benzene extract which contained much of the PAH. The combined extracts were reduced to a convenient volume by a Kuderna-Danish concentrator. The PAH compounds were then isolated by liquid chromatography using silica gel to remove interfering species. The column was packed (methylene chloride slurry) with 10 g of 100-200 mesh silica gel and washed with 40 ml of petroleum ether. A 25 ml fraction of petroleum ether and a 20 ml fraction of 20 percent methylene chloride in petroleum ether were collected and discarded. The PAH were eluted with 75 ml of 20 percent methylene chloride in petroleum ether, followed by 30 ml of 50 percent methylene chloride in petroleum ether. The volume of the PAH fraction was reduced to about 1 ml by use of a Kuderna-Danish concentrator and to a final 0.5 ml by directing a gentle stream of nitrogen across the top of the sample. An internal standard (9-phenylanthracene) was spiked into the reduced sample.

The analytical scheme involved a glass capillary GC/MS procedure which separates many PAH isomers (including benzo(a)pyrene and benzo(e)pyrene) with only one chromatographic run. A 30 m SE-52 capillary column was directly coupled to the mass spectrometer via a glass capillary transfer line. The gas chromatograph was equipped with a Grob-type injector enabling splitless injections. The column was temperature programmed from 160-320°C at 4°C/min. Injector temperature was 300°C while the transfer line was held at 315°C.

The separation efficiency and high temperature stability of high resolution capillary GC is shown in Figure 2 for a standard mixture of PAH compounds. Compounds such as coronene and dibenzopyrenes with boiling points above 520°C are eluted as sharp peaks. Close to baseline separation is achieved for isomeric compounds such as phenanthrene/anthracene, benzo(a)anthracene/chrysene and benzo(a)pyrene/benzo(e)pyrene.

Since the coal extracts were heavily loaded with organics, single ion monitoring was used in the GC/MS analysis to improve sensitivity. The molecular ions of up to three compounds of interest were simultaneously monitored. Quantification was achieved by ratioing the ion current of the molecular ion of interest to that of the differences in ionization efficiencies of the compound and the internal standard. The use of single ion monitoring minimized interferences from fragmentation of extraneous compounds which may not have been removed during the liquid chromatographic cleanup.

The GC/MS system used for the PAH analyses consisted of a Finnigan Model 9500 biomedical type gas chromatograph coupled with a Finnigan Model 3200 mass spectrometer. Data collection and processing was handled by a Finnigan Incos Data System which utilized a Data General Nova 3 computer with 32K of memory.

QUALITY ASSURANCE

Before the sampling and analysis procedures were initiated a quality assurance plan was submitted to the EPA project officer. This plan addressed specific elements of quality control applied to this study in addition to general quality assurance measures that are routinely performed at Battelle to ensure defensibility of analytical results, e.g., periodic instrument audits, defined calibration procedures, and unannounced audits by one of Battelle's QA officers.

Fuel tests were ASTM procedures. Confidence limits measured for duplicate analyses and single determinations in separate laboratories are provided in the ASTM methods. Estimates of repeatability and reproducibility for fuel data supplied by the Vermont Agency of Environmental Conservation are given in Table 2.

Quality control procedures for the gas bulb analyses involved careful daily calibration checks using reference gas mixtures. Quality control and

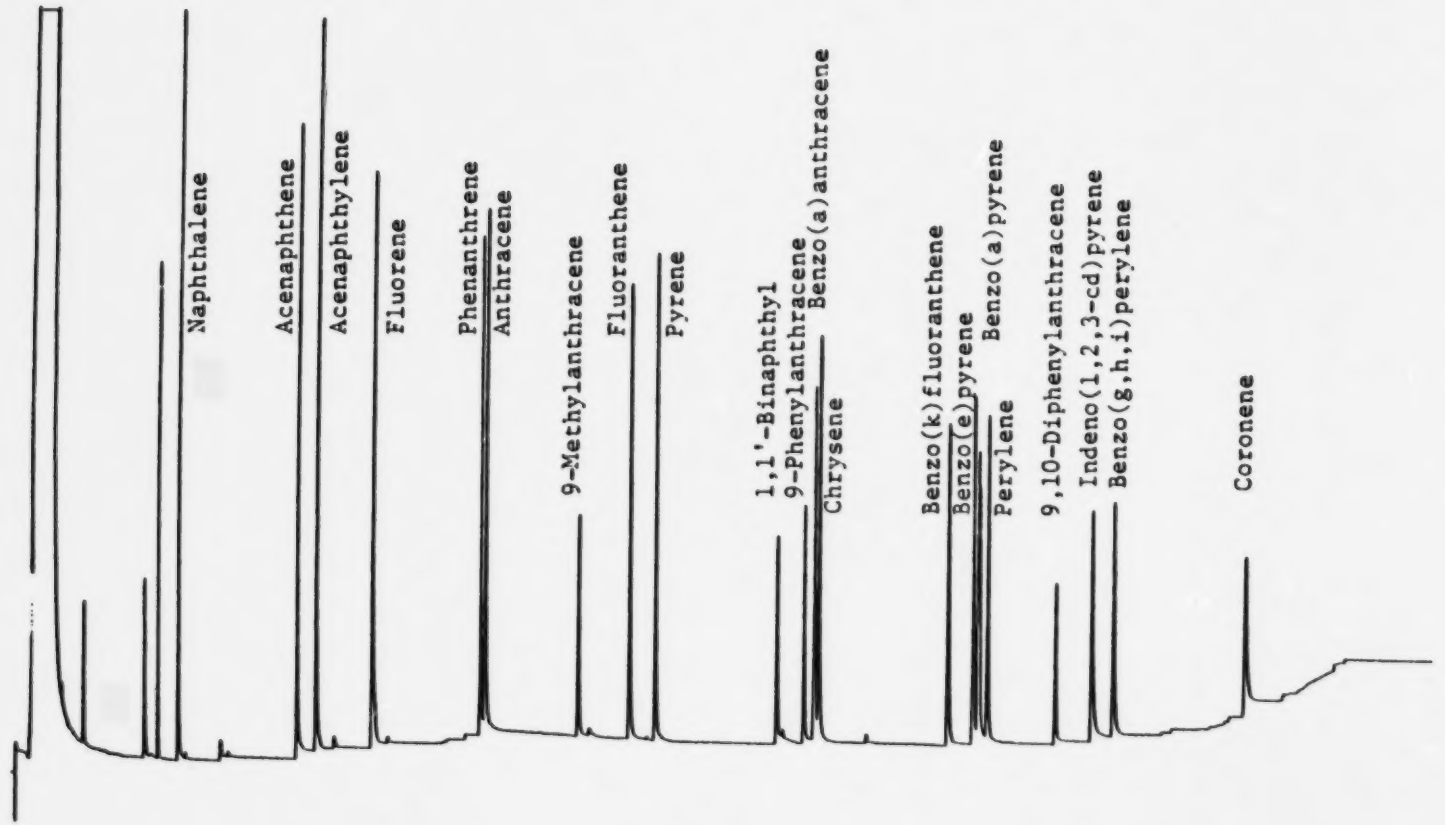

FIGURE 2. GAS CHROMATOGRAM OF PAH STANDARD MIXTURE.

TABLE 2. ESTIMATED REPEATABILITY AND REPRODUCIBILITY FOR ASTM ULTIMATE AND PROXIMATE FUEL TESTS

Test	Method	Repeatability[a]	Reproducibility[b]
Btu gross	D240 (ASTM)	±55 Btu/lb	±175 Btu/lb
Btu net	D240 (ASTM)	±55 Btu/lb	±175 Btu/lb
Moisture (%)	D1744 (ASTM)	±11 ppm	Not determined
Ash (%)	D482 (ASTM)	±(0.007-0.003)	±(0.024-0.005)
Carbon (%)	Combustion TCD	±2%	±2%[c]
Hydrogen (%)	Combustion TCD	±2%	±2%[c]
Nitrogen (%)	Chemiluminescence in toluene	--	--
Sulfur (%)	D129/2622 (ASTM)	0.016 x + 0.006/0.05 times % S	0.037 x + 0.13/0.16 times % S

(a) A 95% confidence interval for the same operator performing duplicate analyses.
(b) A 95% confidence interval for single determinations by each of two laboratories.
(c) Estimate.

quality assurance procedures are documented in the Battelle Chemistry Department's Quality Assurance Plan and daily records were maintained during the study. These records are kept in bound laboratory record books which are microfiched at the end of the study and duplicate copies are stored in fireproof safes in different locations to prevent accidental loss.

Instruments used in gas bulb analyses were checked daily for response performance and calibrated before analyses of samples. Argon was analyzed daily to check the performance of the mass spectrometer, and several standard gases were run to verify sensitivity and fragmentation patterns.

Performance checks and calibration of gas chromatographs were done using standard mixtures of appropriate compounds. The Aerograph, Model 202, gas chromatograph was calibrated with a standard mixture of oxygen, nitrogen, methane, and carbon monoxide, and recorded in the laboratory record book. The Varian, Model 3700, gas chromatograph with flame photometric detector, was standardized with a mixture of hydrogen sulfide, carbonyl sulfide, and carbon disulfide. A separate standard was used for sulfur dioxide. Calibration of the flame ionization detector was conducted with a standard mixture of saturated straight chain hydrocarbons (C_1 through C_4), and a mixture of unsaturated straight chain hydrocarbons (C_1 through C_4). All standard checks were recorded in a laboratory record book.

Quality assurance of GC/MS data included daily tuning and analysis of a standard mixture of PAH. The reference standard was made fresh in distilled-in-glass (DIG) benzene using synthetic standards that had been previously analyzed to establish chemical purity. A recovery standard of d_{12}-benzo(a)-pyrene (BaP) was used to estimate method losses. The d_{12}-BaP was administered to each Soxhlet extractor by liquid injection of 200 µl of a 200 µg/ml solution of the standard in DIG benzene. The amount of this 40 µg spike recovered by quantitative analysis using the 9-phenylanthracene internal standard method was used to estimate losses in analytical preparation. The reported PAH data are corrected for BaP and the other PAH are reported as determined without correction.

SECTION 4

RESULTS

As shown in the stove operation data provided in Table 3, the burn rates during the combustion tests varied between 0.6-1.6 kg/hr and typical gas discharge volumes varied between 44-80 m^3. The relationship between flue gas per unit weight of fuel was computed from the following relationship assuming no residual ash carbon in residue.

$$\text{Dry Gas (kg)/Fuel(kg)} = \frac{11CO_2 + 8O_2 + 7(N_2 + CO)}{3\ (CO_2 + CO)} \times \left[(C + 3/8\ S) + 5/8\ S)\right]$$

The results of fuel analyses are given in Table 4. The stoker grade bituminous coal was used only to test the modified wood stove. Nut grade bituminous and pea grade anthracite were used in all other tests.

The effect of fuel type and size is clearly seen in the particulate and condensible organics emission levels shown in Table 5. In every case, the bituminous coal gave much higher emission levels than anthracite. This difference is expected from the two coal types but the magnitude of the difference in emission levels between the two coals is surprising. No attempt is made to differentiate the impact of coal grade from the effects caused by fuel type (anthracite versus bituminous).

The results of the volatile analyses for the anthracite and bituminous tests are shown in Tables 6 and 7, respectively. For most of the compounds detected the sensitivity of gas mass spectrometry and gas chromatography with selective detectors is about 1-50 ppm (V/V). In the anthracite tests, emissions from the modified wood stove were found to have higher methane and NO_x levels than emissions from the coal stove. The coal stove generated much higher SO_2 levels than the modified wood stove, by a factor of ten, when burning anthracite.

TABLE 3. STOVE AND SAMPLING PARAMETERS

Stove Parameters	Bituminous Coal Stove High Burn Rate	Anthracite Coal Stove High Burn Rate	Bituminous Coal Stove Low Burn Rate	Anthracite Coal Stove Low Burn Rate	Bituminous Modified Wood Stove Low Burn Rate	Anthracite Modified Wood Stove Low Burn Rate
Fuel per Test, kg (lb)	2.5 (5.6)	2.8 (6.2)	1.7 (3.8)	1.3 (2.9)	2.4 (5.4)	1.7 (3.7)
Burn Rate, kg/hr (lb/hr)(a)	1.3 (2.6)	1.6 (3.1)	0.7 (1.7)	0.6 (1.5)	1.0 (2.6)	0.7 (1.8)
Mean Stack Temperature, C(F)(b)	270 (520)	250 (480)	220 (420)	140 (278)	160 (315)	140 (280)
Sampling Time, min	120	120	150	155	155	155
Stack Water, percent	1.8	3.5	1.8	1.6	1.9	2.3
Stack Oxygen, percent(c)	13	10	17	17	14	13
Stack Carbon Dioxide, percent(c)	6	10	4	3	6	7
Stack Carbon Monoxide, percent(c)	0.6	0.6	0.2	0.0	0.4	0.4
Method 5 Volume (dry), SCM (SCF)	1.8 (64)	1.9 (68)	2.0 (70)	2.4 (85)	2.3 (81)	2.5 (87)
Total Stack Discharge, Q, SCM (SCF)	64 (2,300)	58 (2,050)	72 (2,500)	80 (2,800)	67 (2,400)	44 (1,600)

(a) Averaged over total test.
(b) At Method 5 probe.
(c) Approximate, values determined by ORSAT technique.

TABLE 4. FUEL PARAMETERS

	Anthracite (Pea)(a)	Bituminous (Nut)(a)	Bituminous (Stoker)(a)
Ultimate Analyses			
Carbon, percent (W/W dry)	85.8	79.1	80.6
Hydrogen, percent (W/W dry)	1.9	5.2	5.3
Nitrogen, percent (W/W dry)	0.7	1.5	1.6
Oxygen, percent (W/W dry)	0.1	6.9	4.9
Sulfur, percent (W/W dry)	0.4	0.8	0.8
Ash, percent (W/W dry)	8.9	3.2	5.5
Proximate Analyses			
Fixed Carbon, percent (W/W dry)	85.6	56.5	56.2
Volatiles, percent (W/W dry)	3.3	37.0	37.0
Moisture, percent (W/W dry)	2.2	3.3	1.3
Heating, value, dry basis, ash free, J/kg (Btu/lb)	3.5×10^7 (14,900)	3.5×10^7 (15,100)	3.4×10^7 (14,400)

(a) Fuels are graded by diameter range to pass a circular mesh sieve: Pea Grade = 1.4 cm - 2.1 cm; Nut Grade = 3.2 cm - 5.1 cm; Stoker Grade = 1.9 cm - 3.2 cm.

TABLE 5. PARTICULATE AND CONDENSIBLE ORGANIC EMISSIONS

Stove	Coal	Burn Rate (kg/hr)(a)	Particulates-Method 5 (mg/SCM)	(ng/J)	(g/kg)	Condensible Organics(b) (mg/SCM)	(ng/J)	(g/kg)
Coal	Bituminous	High (1.3)	458	1.8×10^{-1}	6.2	98	3.9×10^{-2}	1.3
Coal	Anthracite	High (1.6)	8	2.4×10^{-3}	0.08	3	9.2×10^{-4}	0.03
Coal	Bituminous	Low (0.7)	176	1.1×10^{-1}	3.8	128	7.8×10^{-2}	2.7
Coal	Anthracite	Low (0.6)	6	4.2×10^{-3}	0.13	2	1.4×10^{-3}	0.04
Wood	Bituminous	Moderate (1.0)	197	7.1×10^{-2}	2.2	66	2.4×10^{-2}	0.75
Wood	Anthracite	Low (0.7)	8	2.5×10^{-3}	0.08	8	2.5×10^{-3}	0.08

(a) Corrected for ash.
(b) Gravimetric determination of XAD-2 collected organics.

TABLE 6. PRINCIPAL VOLATILE EMISSIONS--ANTHRACITE TESTS
(ppm, V/V)

	Coal Stove		
	High Burn	Low Burn	Modified Wood Stove
Methane	100	100	630
Ethene	1	0.2	0.8
Ethane	1	--	2
Propene	--	--	--
Propane	--	--	2
1-Butene	--	--	--
SO_2	350	290	25
COS	--	--	23
CS_2	--	0.2	--
H_2S	--	--	6
NO_x	--	--	100

-- = Not detected.

In tests with bituminous fuel, the coal stove had much higher levels of methane and ethene than the modified multifuel stove designed primarily for wood burning. Comparing the sulfur oxide data from this study with results of earlier EPA coal stove tests is very interesting. The industrial coal stoker boiler study firing bituminous coal (2) reported SO_x levels of 90-490 g/kg fuel-dry basis (180-970 lb/ton) with a mean of 227 g/kg (450 lb/ton) for 21 stokers tested. The stoker fed residential units cited earlier (1) found SO_x levels of 3-15 g/kg (6-30 lb/ton) for ten tests with a mean of 9.5 g/kg (19 lb/ton). Bituminous coal was used in both studies and each study showed a linear relationship between available fuel sulfur and SO_x emissions. In this

TABLE 7. PRINCIPAL VOLATILE EMISSIONS--BITUMINOUS TESTS
(ppm, V/V)

Bituminous	Coal Stove		Modified Wood Stove
	High Burn	Low Burn	
Methane	210	590	95
Ethene	722	1000	61
Ethane	2	--	--
Propene	2	--	0.4
1-Butene	--	3	--
SO_2	208	300	430
COS	--	3	1
CS_2	--	--	0.3
NO_x	--	--	160

-- = Not detected.

study the three bituminous tests yielded values of 13 g/kg (fuel basis-dry-ash free) for the high burn rate coal stove, 32 g/kg for the companion low burn rate test, and 29 g/kg for the modified wood stove burning bituminous coal. Thus, the residential units tend to produce lower SO_x levels than larger industrial units. These lower levels are probably caused by lower fuel-bed temperatures which enable the alkali in the coal ash to capture sulfur as stable sulfates. The temperatures in industrial units are often too high to capture much sulfur because sulfates are unstable.

Polynuclear aromatic hydrocarbon emissions from coal combustion sources were summarized in 1967 in a paper by Hangebrauck, von Lemden, and Meeker (6). These researchers graphically illustrated relative PAH emissions from several sources by using BaP as a key indicator compound. They reported BaP concen-

trations as a function of gross heat input to the furnace. Their graphical presentation of PAH emissions is reproduced in Figure 3. In this figure, efficiency in coal combustion is shown to reduce BaP levels. Thus, large utility furnaces with very high bed temperatures, secondary air, and sufficient excess air produce far less BaP per unit of fuel burned than highly inefficient residential units. Even though Hangebrauck et al. summarized data from the 1960s, the relationship of PAH emissions to combustion efficiency is still valid and has been verified many times. The Vermont study provided an opportunity to measure specific PAH compounds including BaP with modern analytical techniques and good quality control procedures.

Benzo(a)pyrene (BaP) data are given in units of discharge gas, fuel consumed, and thermal output in Table 8. This table also gives thermal input to the furnace in units of Btu/hr ($x10^{-4}$) consistent with the Hangebrauck curve shown in Figure 3. Referring back to Figure 3, the Vermont bituminous coal stove data fall on the line for residential units but the anthracite data fall well outside the coal curve. This deviation is indicative of the observed reductions in PAH emissions through the use of anthracite fuel. The emission data for a representative series of PAH compounds are given in Table 9 for anthracite tests and Table 10 for bituminous tests. The magnitude of PAH emissions can be compared between sources by using consistent units. An Electric Power Research Institute study has suggested using weight of analyte per Joule as a unit for reporting PAH results (7). Several sources including coal and wood-fired residential units are compared in Table 11 using this unit as a basis for comparison. Residential coal combustion (using bituminous coal) shows the highest emissions of BaP relative to other coal-burning combustion systems compared. This observation is consistent with the Hangebrauck curve. Anthracite fuel was found to generate far lower BaP emissions than bituminous coal in equivalent appliances. Although coal gasification (9) and perhaps other coal processes may result in BaP emission levels that are higher than residential coal combustion, the high levels observed in residential coal combustion should not be ignored. The magnitude of the BaP and other PAH discharges found in this study, together with the high particulate and SO_x levels, should be considered in light of the current increased use of bituminous coal for residential space heating. The values reported in this study

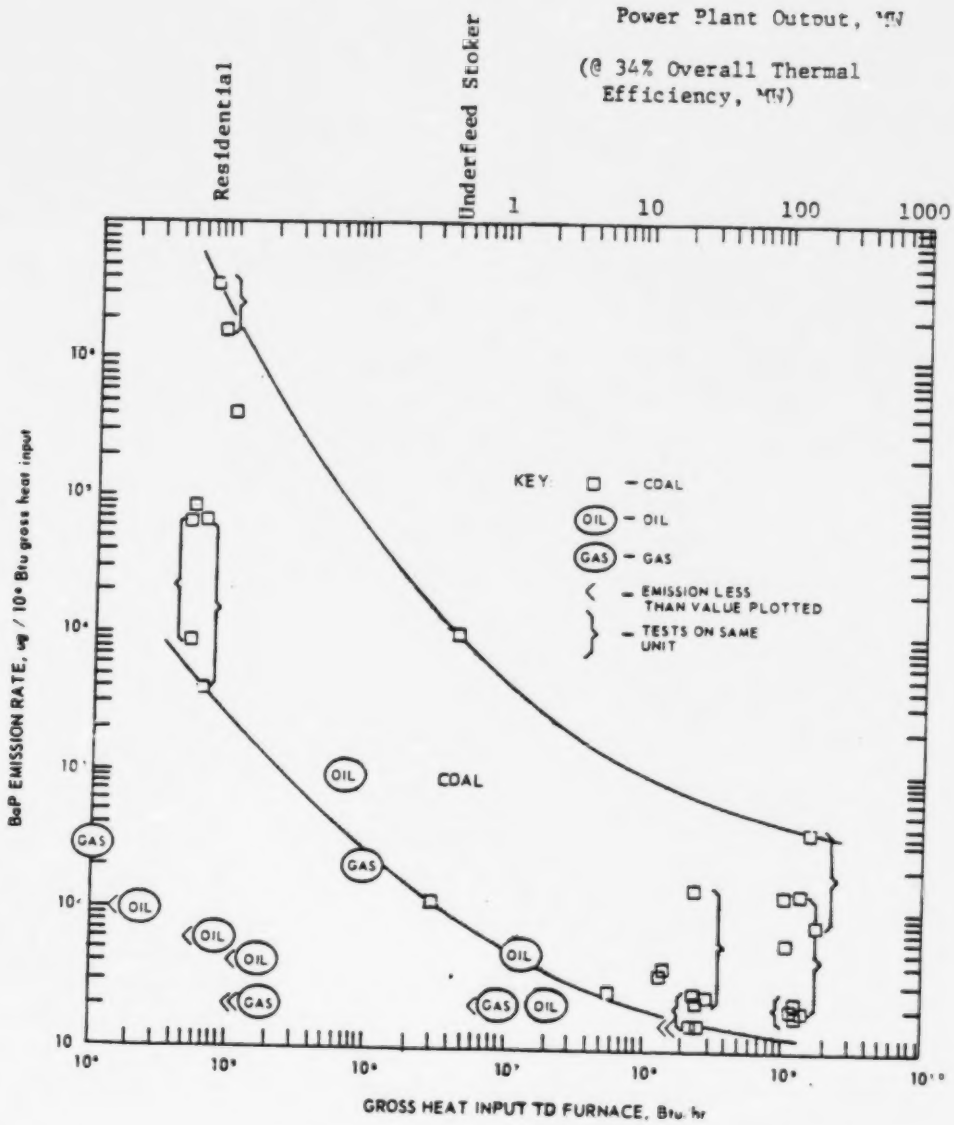

FIGURE 3. RANGE OF BENZO(a)PYRENE EMISSIONS FROM COAL, OIL, AND NATURAL GAS HEAT-GENERATION PROCESSES (Reproduced from Reference 5).

TABLE 8. BENZO(a)PYRENE CONCENTRATIONS IN VERMONT COAL STOVE STUDY

Emission	Bituminous Coal Stove High Burn	Anthracite Coal Stove High Burn	Bituminous Coal Stove Low Burn	Anthracite Coal Stove Low Burn	Bituminous Modified Wood Stove Low Burn	Anthracite Modified Wood Stove Low Burn
Gaseous Emission (μg/SCM)	110	0.1	52	0.08	120	0.17
Fuel Based Emission (ppb-dry-ash free)	2800	3	1700	5	3400	4
Thermal Based Emission (ng/J)	8.1×10^{-2}	7.3×10^{-5}	5.0×10^{-2}	1.5×10^{-4}	9.8×10^{-2}	1.2×10^{-4}
Thermal Input to Furnace (Btu/hr)	4.2×10^{4}	4.7×10^{4}	2.2×10^{4}	1.7×10^{4}	3.0×10^{4}	2.1×10^{4}

TABLE 9. POLYNUCLEAR AROMATIC HYDROCARBON EMISSIONS--ANTHRACITE TESTS (μg/SCM)

	Coal Stove High Burn Rate	Coal Stove Low Burn Rate	Modified Wood Stove Low Burn Rate
Naphthalene	5.3	0.08	14.(a)
Acenaphthene	0.94	0.12	0.82
Acenaphthylene	0.99	0.12	6.3
Fluorene	0.89	0.08	1.2
Phenanthrene	11.	0.81	9.0
Anthracene	1.2	0.08	0.9
Fluoranthene	8.7	0.85	4.7
Pyrene	6.3	0.48	3.7
Benzo(a)anthracene	5.4	0.12	1.1
Chrysene	5.9	0.20	1.5
Benzo(k)fluoranthene	0.68	0.12	1.3
Benzo(e)pyrene	0.16	0.04	0.30
Benzo(a)pyrene	0.10	0.08	0.17
Perylene	0.02	0.02	0.04
Indeno(1,2,3-c,d)perylene	0.37	0.04	0.17
Benzo(g,h,i)perylene	0.31	0.04	0.09
Anthanthrene	0.005	0.01	0.02
Coronene	0.21	0.01	0.13

(a) Saturated.

TABLE 10. POLYNUCLEAR AROMATIC HYDROCARBON EMISSIONS--BITUMINOUS TESTS (µg/SCM)

	Coal Stove High Burn Rate	Coal Stove Low Burn Rate	Modified Wood Stove Moderate Burn Rate
Naphthalene	830	210	330(a)
Acenaphthene	120	19	70
Acenaphthylene	1,100	16	330(a)
Fluorene	210	90	210
Phenanthrene	780	180	330(a)
Anthracene	210	100	160
Fluoranthene	360	76	270
Pyrene	210	69	190
Benzo(a)anthracene	130	46	170
Chrysene	150	37	140
Benzo(k)fluoranthene	190	92	280
Benzo(e)pyrene	100	38	85
Benzo(a)pyrene	110	52	120
Perylene	13	5	16
Indeno(1,2,3-c,d)perylene	14	36	150
Benzo(g,h,i)perylene	49	24	72
Anthanthrene	4	7	27
Coronene	60	9	42

(a) Saturated.

TABLE 11. BENZO(a)PYRENE EMISSIONS FROM COMPARATIVE COMBUSTION SOURCES (pg/J)

	Wood-Fired Residential Heaters(a)	Bituminous-Fired Residential Heaters(b)	Anthracite-Fired Residential Heaters(b)	Bituminous-Fired Industrial Boilers(c)	Oil-Fired Utility Boilers(c)
Range	8.3×10^{3}-10^{-4}	98-50	0.15-0.07	0.14-0.005	4×10^{-4}
Average	1.8×10^{3}	76	0.11	0.07	4×10^{-4}
Number of Tests	5	3	3	15	(not given)

(a) Reference 8.
(b) This study.
(c) Reference 7.

represent a very small data base, thus this work should be considered a contribution to the literature in the field instead of a comprehensive evaluation of these combustion systems.

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